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PHOTOVISCOUS TECHNIQUE DEVELOPMENT

Volume II - Photoviscous Test Stand

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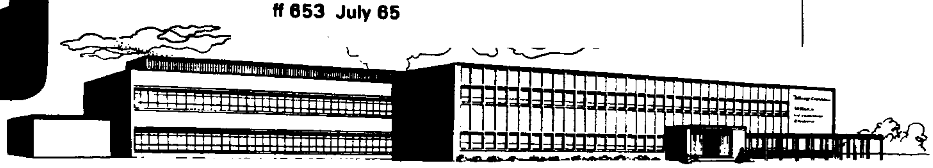

RESEARCH LABORATORIES DIVISION

SOUTHFIELD, MICHIGAN

Report No. 3477

PHOTOVISCOUS TECHNIQUE DEVELOPMENT

Volume II - Photoviscous Test Stand

15 June 1966

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ABSTRACT

This project concerned the application of photoviscosity to experimental investigations of flow fields in fluid devices. Milling Yellow dye solutions were used in the experiments. The analytical relationships between the optical phenomena and two-dimensional flow kinematics were summarized and presented. Test equipment was developed for applying the photoviscous technique to a variety of transparent models simply and conveniently. The use of a rectangular channel model, integral with the fluid circulation system, was demonstrated as a calibration device for obtaining the optic response of the photoviscous liquid.

The majority of the quantitative testing was performed using a vortex model with no tangential flow. A comparison was made of the radial distribution of the fluid deformation rate as determined (a) analytically, and (b) by photoviscous experiments. The agreement was poor, which is attributed to the low aspect ratio (depth-to-width ratio) of the model. The comparison demonstrated (a) the importance of the aspect ratio criterion, if quantitative determination of a flow field is of interest, and (b) the need for studying the three-dimensional stress-optic law for Milling Yellow dye solution to extend the utility of the technique.

The combination of photoviscosity with high-speed motion picture photography was found to be a potentially valuable technique for studying the internal dynamic response times in fluid flow models. Several kinds of qualitative information obtainable, using photoviscosity, are described. Recommendations are made for adding rheological calibration to optical calibration of the working fluid to refine the photoviscous technique.

FOREWORD

This report was prepared by the Research Laboratories Division of the Bendix Corporation as part of the research and study performed under Contract NAS 8-5407, Phase III, "Development of a Photoviscous Technique for Fluid Flow Studies," for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration.

The project engineer for the Marshall Space Flight Center was Mr. Jerry A. Peoples.

The technical work performed at the Bendix Research Laboratories Division was the responsibility of Mr. F. M. Faubert. The project work was initiated by Mr. B. S. Fichter, who made many contributions throughout the project duration. The work was performed in the Applied Mechanics Department, headed by Mr. B. R. Teitelbaum.

The report is published in two volumes. Volume I - Theory and Experiments treats the analytical foundation of the photoviscous technique and describes the results of experiments performed during the project. Volume II - Photoviscous Test Stand describes the equipment developed during the project, and gives operating and maintenance information.

SECTION 1

INTRODUCTION

Description of Apparatus

The Bendix Photoviscous Test Stand is a laboratory test facility which provides a convenient method of obtaining quantitative and qualitative data from two-dimensional transparent test models. This flow visualization technique utilizes the birefringent properties of Milling Yellow dye solutions. The stand is equipped with an optical system that can provide either white or monochromatic light, in either the plane or circularly-polarized mode. The flow circulation system will provide variable volume flow rates, at various constant temperatures. An overall view of the test stand is shown in Figure 1-1.

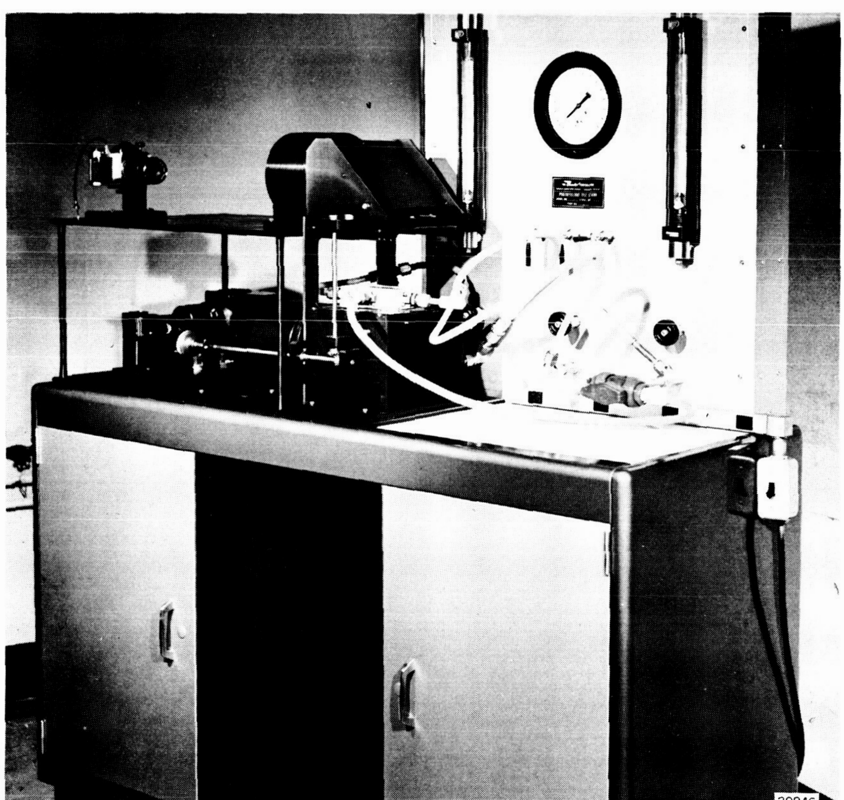

Figure 1-1 - Bendix Photoviscous Test Stand

The base of the stand is composed of two modular enclosures connected by a working surface. These components are commercially available from Amco Corporation. The two modular enclosures house the flow circulation components. The working surface supports the optical system superstructure, the polaroid fixture, and the gage panel. These last three items were built specifically for the system.

Flow Circulation System

The flow circulation system contained in the test stand is shown schematically in Figure 1-2, and Figures 1-3 and 1-4 show the components as installed in the modular enclosures. The motive source of power for the system is a centrifugal pump and motor combination, manufactured by Oberdorfer Company. The motor delivers 0.33 horsepower at 3450 rpm, and the pump will deliver 17 gallons per minute at 10 psig discharge pressure. (This rating is for water at 68°F.) The impeller and the pump housing are bronze.

The temperature of the Milling Yellow dye is regulated by a Jordan mixing valve and temperature sensor, and a Vickers shell-and-tube heat exchanger. A section view of the mixing valve is shown in Figure 1-5.

The temperature regulation uses the feedback principle. From the figure, we see that the desired temperature setting is obtained by positioning a spring Ks which varies the load on diaphragm A_1. Assume the valve is at steady-state. Now if a small decrease in the dye solution temperature T_f should occur, the pressure P_1 will decrease a corresponding amount. Alternatively, an increase in the valve setting T_{set} can be made manually. Either case violates the force balance between the pressure P_1 times the area A_1 of the diaphragm, and the spring load. Due to the resulting unbalance, the diaphragm will move up until a force equilibrium is achieved. The motion of the diaphragm is transmitted directly to the sliding valve, which, as shown in Figure 1-5, causes an increase in the valve area for the hot water flow and a decrease in the valve area for the cold water flow. Due to the net increase in enthalpy of the output flow to the heat exchanger, an increase in dye solution temperature is effected. The temperature of the solution continues to increase, until the fluid in the sensor reaches a temperature level that produces a pressure force great enough to substantially overcome the initial force unbalance. The valve has now reached a new steady-state position with the error between command and actual fluid temperatures at a very small value.

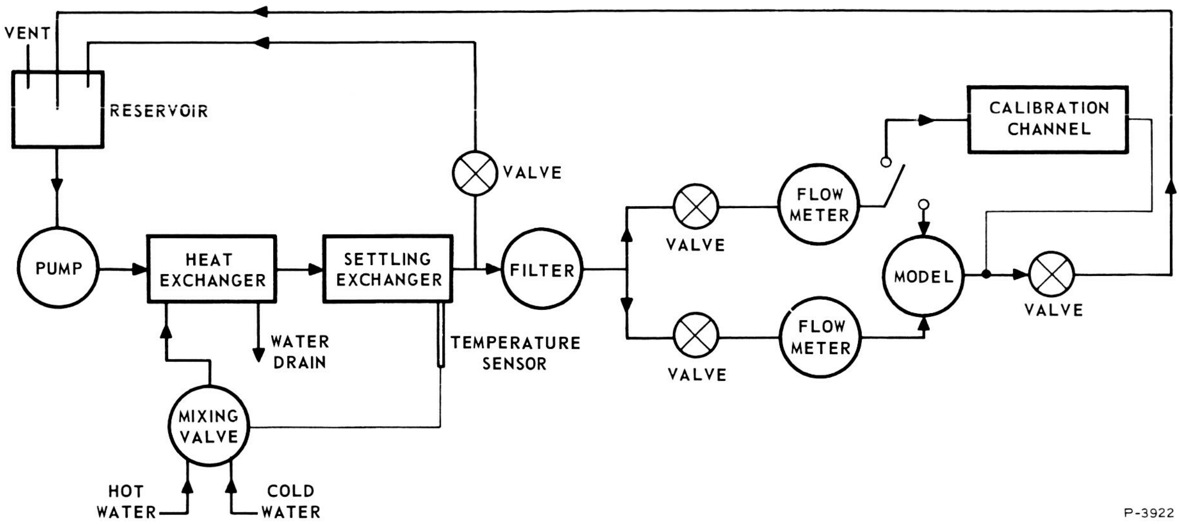

Figure 1-2 - Schematic of Flow Circulation System

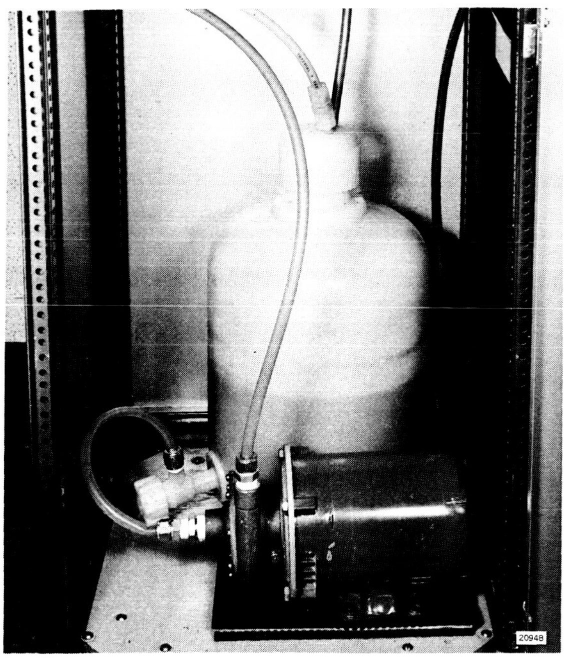

Figure 1-3 - Right Hand Cabinet Reservoir and Pump Motor Combination is Installed

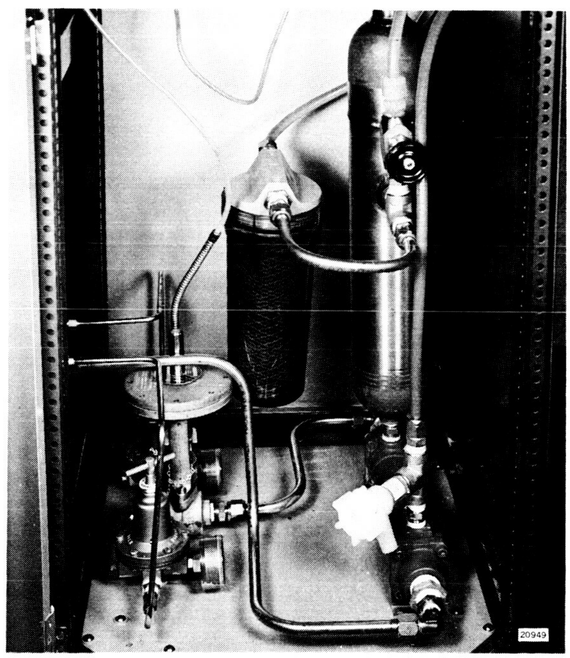

Figure 1-4 - Left Hand Cabinet Mixing Valve, Heat Exchanger Settling Tank and Filter as Installed

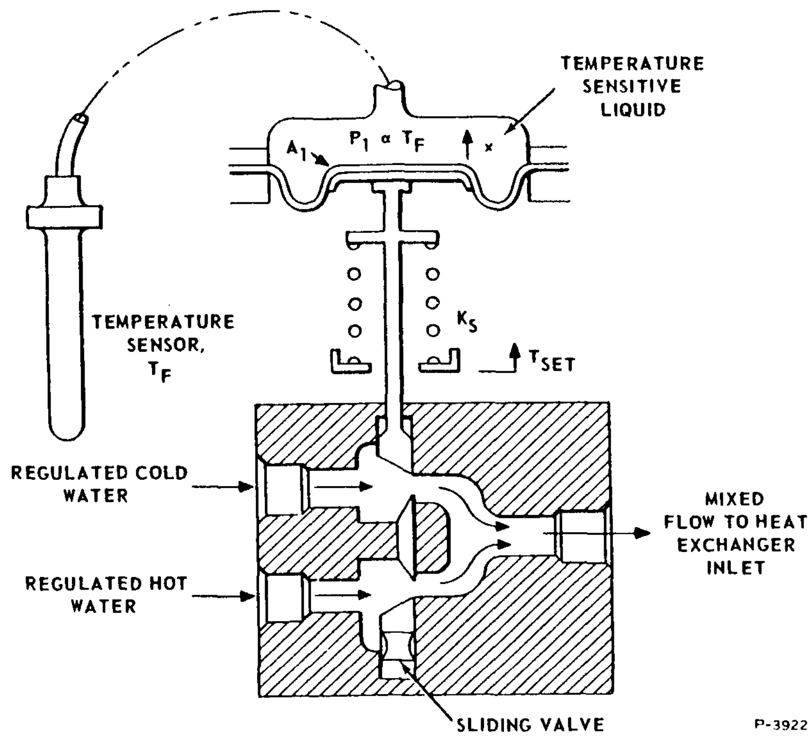

Figure 1-5 - Jordan Mixing Valve

The cold and hot water is supplied to the valve by Norgren pressure regulators, which tend to hold a constant differential pressure across the sliding valve. It can be seen that the feedback principle,used in regulating the temperature,will also minimize changes in dye solution temperature due to variations in water temperature.

The output from the heat exchanger flows into the settling chamber. The chamber is a stainless steel cylinder with a 1.5 gallon capacity. The settling chamber is used to decrease the fluid velocity, so that the temperature as sensed by the temperature sensor will be as accurate as possible.

The output flow from the settling chamber can be bypassed back to the reservoir or directed to the test model. The flow to the test model can be split into two supply lines. Each supply line has its own flowmeter, and the supply pressure in each line can be measured. The flowmeters are manufactured by Fischer-Porter Company and are calibrated in percent of volume flow. At 25°C, the 100 percent flow point corresponds to 5.85 cubic inches per second of water. The tube assemblies are made of stainless steel and glass, and the floats are of stainless steel.

The supply tank, or reservoir, is a purchased item from Tamco Products. The tank and spigot are made of polyeurethane, and the tank has a five gallon capacity. The return lines from the model and the bypass valve enter the tank through drilled holes in the cap. The holes are slightly larger than the tube diameters, so that the tank will be vented essentially to atmosphere, while minimizing the amount of dye evaporation.

The lines and fittings connecting the flow circulation components are stainless steel and plastic. All of the dye flowing through the model is filtered down to 40 microinches by a Culligan water filter, located on the discharge side of the settling tank.

Optical System

The optical system of the Bendix Photoviscous Test Stand is shown schematically in Figure 1-6, and the actual apparatus arrangement is shown in Figures 1-7 and 1-8. The system is comprised of three basic subsystems: the lower level optics, the polaroid fixture and the upper level optics. These subsystems will be discussed in the same order.

The lower level optics subsystem produces a collimated beam of white or monochromatic light. The light source used is a 150-watt projection bulb. A heat filter and a cooling fan are integrated into the light source. The heat filter removes that part of the spectrum in the infra-red region, while the cooling fan provides circulation of air around the bulb.

The white light produced by the light source is transmitted through a focusing lens and, if desired, through a monochromatic filter. The focusing lens is used to provide an intense beam of light at the first surface mirror. The monochromatic filter passes only the green wavelength in the white light, and can be removed easily from the optical path if white light is desired.

The beam of light coming from the first surface mirror is directed into a collimating lens which produces a collimated bundle of light rays; that is, there is no convergence or divergence of the light beam.

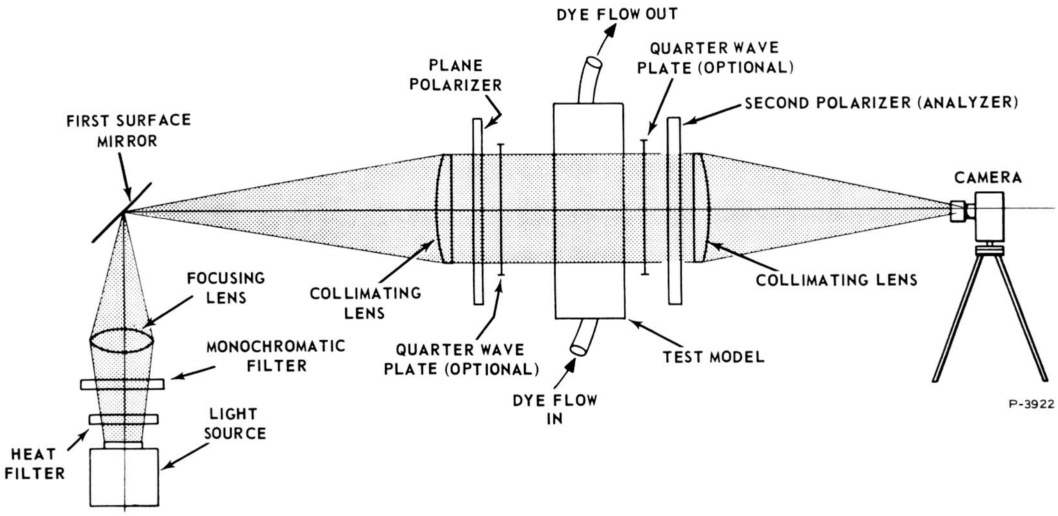

Figure 1-6 - Schematic of Optical System

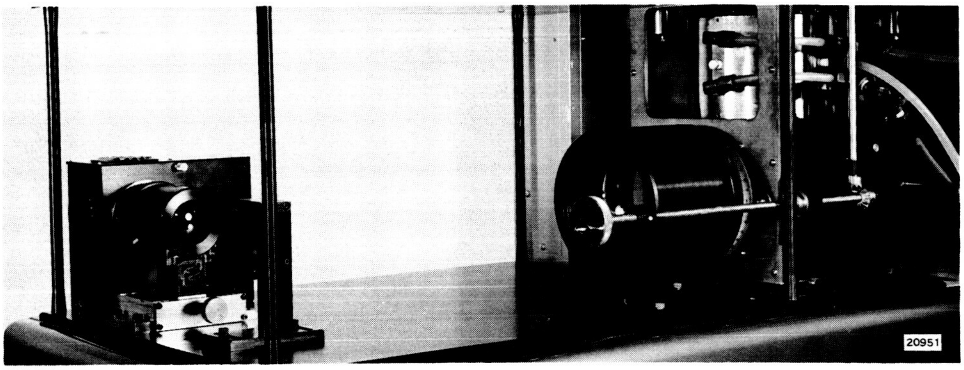

Figure 1-7 - Lower Level Optics and Polaroid Fixture

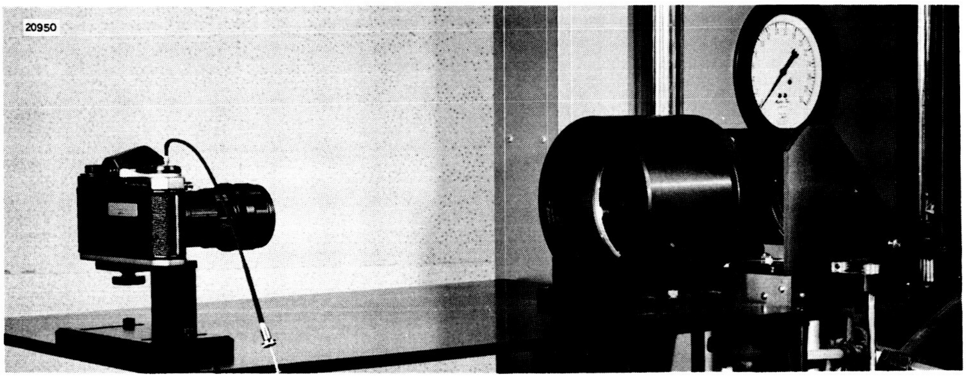

Figure 1-8 - Upper Level Optics and Polaroid Fixture

The polaroid fixture is composed of a polarizer, two first surface mirrors, and an analyzer. The collimated beam from the lower level collimator passes through the polarizer, and is reflected upward through the test model by the first mirror. The light from the model then passes through an analyzer, and is reflected through another 90-degree turn by the second mirror. The polarizer and analyzer sheets are purchased items from the Polaroid Corporation and are designed to give either plane or circularly-polarized light. The polaroid sheets are manufactured with quarter wave layers bonded to one side. If the sheets are oriented so that the quarter wave plate is ahead of the polarizer and behind the analyzer, plane-polarized light is obtained. If both sheets are reversed, circularly-polarized light is obtained. The polaroid fixture is equipped with a gear system driven by a hand crank, so that the polarizer and the analyzer can be rotated together. The position of the polarizer axis can be measured with reference to the horizontal by a 360-degree calibration dial located on the front face of the fixture. The test model is positioned in the polaroid fixture, centered between the polarizer and the analyzer.

The upper level optics subsystem is equipped with a collimating lens and a fixture for holding a camera or a projecting lens. The collimator focuses the light beam from the polaroid fixture geometrically at the camera fixture.

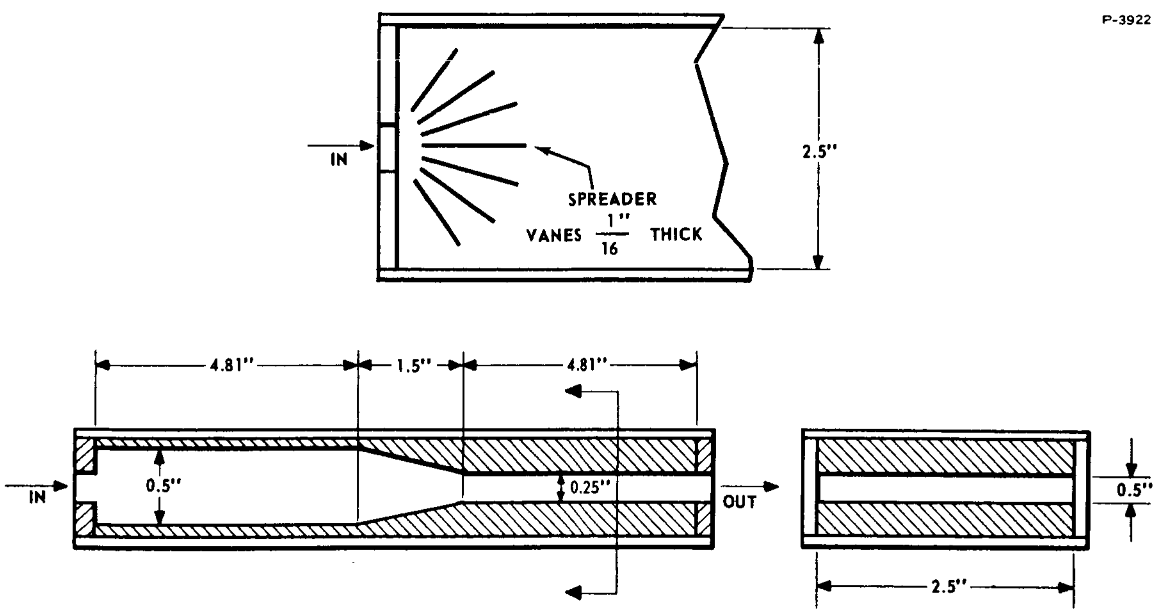

Figure 1-9 - Rectangular Channel Dimensions

The camera used for all of the experimental work performed at the Bendix Research Laboratories was a Honeywell 35 mm single lens reflex, equipped with a 55 mm focal length f/2 Takumar lens, in combination with a Spiratone 3X Telextender lens. All of the monochromatic patterns were recorded with Kodak Tri-X film, ASA-400. The color patterns were recorded with Kodacolor-X film, ASA 64.

Calibration Fixture

The test stand is equipped with a high aspect ratio rectangular channel which is used to obtain the optic response of the dye solution. The channel is fabricated from plexiglass, and the joints are bonded together with clear cement. The channel is shown in Figure 1-9.

SECTION 2

THEORY OF OPERATION

The utilization of a photoviscous fluid to obtain qualitative and quantitative data from generalized two-dimensional, laminar flow fields is based on the doubly-refracting characteristics of certain fluids. This double refraction characteristic is produced by local shearing stresses, resulting in the formation of two mutually-perpendicular optic axes in the fluid. The orientation of these axes are related to the direction of the maximum rate of deformation in the fluid.

When a birefrigent fluid is caused to flow through a transparent model and is viewed in plane-polarized monochromatic light, visible fringe patterns are formed, which appear as alternate light and dark bands throughout the fluid. It can be shown that the conditions for zero light transmission correspond to

$$\beta = N\left(\frac{\pi}{2}\right) \qquad N = 0, 1, 2, \ldots \qquad (2.1\ a)$$

$$\delta = 2\pi N \qquad N = 0, 1, 2, \ldots \qquad (2.1\ b)$$

where

β = angle between the optic axis and the axis of polarization

δ = relative retardation between the slow and fast rays produced by double refraction.

The dark bands produced by condition (2.1 a) are called isoclinics, and these bands are loci where one of the local optic axes of the fluid is aligned with the direction of vibration of the polarized incident light. The bands produced by condition (2.1 b) are called isochromatics, and are the loci where the relative retardation between the fast and slow rays is either zero or some whole multiple of the wavelength of the incident light.

It should be noted that plane-polarized white light will produce dark bands only as a result of condition (2.1 a), since the light consists of a continuum of wavelengths, and no single phase difference is obtained.

(There will, however, be one dark band formed by condition (2.1 b) for $N = 0$, which is the zero order fringe.) The use of circularly-polarized monochromatic light eliminates any possibility of dark spaces occuring from a condition corresponding to equation (2.1 a), since the entering ray vector has no special orientation with respect to the fluid optic axes. Thus, the use of circularly-polarized monochromatic light eliminates the isoclinics.

The amount of birefringence in a doubly-refracting fluid can be expressed as the difference in indices of refraction between the ordinary and the extraordinary rays, and can be calculated from

$$|n_e - n_o| = \lambda \mu M E_{max} \tag{2.2}$$

where

μ = fluid viscosity

λ = wavelength of the monochromatic light source

M = Maxwell constant

E_{max} = maximum deformation rate in the fluid

n_e, n_o = extraordinary and ordinary indices of refraction

Alternately, the birefringence can also be expressed as

$$|n_e - n_o| = \frac{N \lambda}{L} \tag{2.3}$$

where

L = optical path thickness through the fluid

N = fringe order ($N = 0, 1, 2, 3 \ldots$)

Equating equations (2.2) and (2.3) gives

$$N = \mu M E_{max} L \tag{2.4}$$

which indicates that the amount of deformation rate existing in the fluid is related to the isochromatic fringe patterns formed in the fluid.

The classical method of experimentally determining the relation between fringe order N and maximum deformation rate is by utilizing a concentric cylinder polariscope. This device consists of two concentric cylinders with transparent end plates, and the outer cylinder is connected to a drive system which rotates this cylinder at various speeds. The annular space between the two cylinders is filled with a sample of the test fluid, and the annular gap is illuminated with monochromatic polarized light. The actual test calibration is obtained by noting the cylinder speeds at which different order fringes pass through the center of the annular gap. (A more complete description of the polariscope can be found in Volume I of this report, Section 3.3.)

The fluid calibration curve can also be obtained from the fringe patterns formed in a rectangular channel of high aspect ratio. In practice, this method is definitely more convenient, since a fluid sample does not have to be drawn from the system. The channel can be plumbed directly into the flow circulation system in either series or parallel with the model. The deformation rate existing at any point in the channel, (assuming fully developed laminar flow with constant viscosity) is given by

$$E_{max} = 3\left(\frac{Q}{A}\right)\frac{y}{h^2} \tag{2.5}$$

where

Q = volume flow rate through the channel,(in^3/sec)

A = cross-sectional area of the channel section under consideration (in^2)

h = channel half height, (in.)

y = distance from channel centerline to any point in the flow field, (in)

E_{max} = deformation rate (sec^{-1})

By noting the positions of the fringes with respect to the channel centerline, and calculating the deformation rate, using equation (2.5), at these positions, a plot of fringe order versus deformation rate is obtained. Then from equation (2.3), the fluid birefringence can be calculated for each fringe, giving a final relation of birefringence versus deformation rate for the test fluid.

The necessity of obtaining the birefringence, $n_e - n_o$, versus deformation rate, E_{max}, becomes apparent when we consider that both the velocity gradient and the stream function ψ are related to the maximum deformation rate existing in the fluid. The velocity distribution is related to the deformation rate by equation (2.6), while the relationship between stream function ψ and deformation rate is given by equation (2.7) These equations are

$$\frac{\partial V}{\partial n} = \frac{V}{r} \pm \sqrt{E_{max}^2 - \frac{4V^2}{r'^2}} \tag{2.6}$$

where

$\frac{\partial V}{\partial n}$ = velocity gradient along a normal to a set of streamlines, (sec^{-1})

V = velocity along a streamline (in/sec)

r = radius of curvature of stream line (in)

r' = radius of curvature of a normal to a set of streamlines (in)

and

$$E_{max} = \sqrt{\left(-2\frac{\partial^2\psi}{\partial x \partial y}\right)^2 + \left(\frac{\partial^2\psi}{\partial y^2} - \frac{\partial^2\psi}{\partial x^2}\right)^2}, \tag{2.7}$$

where

ψ = Stokes stream function (in^2/sec)

x, y = rectangular coordinates (in)

Essentially, the presence of E_{max} in these equations is the basis of the photoviscous technique when used to obtain quantitative data. The values of E_{max} can be obtained throughout the flow field from the isochromatic fringe patterns. This is done by mapping the lines of constant fringe order and calculating the value of birefringence corresponding to each locus. Then the value of deformation rate corresponding to the various values of birefringence can be taken directly from the calibration curve, which was obtained with the rectangular channel.

The utility of equations (2.6) and (2.7) should be discussed at this point. It can be seen from equation (2.6) that the values of the radii of curvature of both the streamline and the normal to a set of streamlines are needed before the equation can be graphically or numerically integrated to obtain the velocity distribution. In essence, this means that the streamlines must be known previously, or else obtained by some other method, such as dye injection. Equation (2.7), however, is completely general, although the solution to the equation requires that it be put in finite difference form before it can be solved by numerical techniques. The boundary conditions are obtained from a fluid flow consideration that ψ is constant along any boundary.

SECTION 3

OPERATION

The Bendix Photoviscous Test Stand is designed to provide simplicity in operation. The following list indicates the entire sequence of events necessary to produce visible fringe patterns.

1. Connect plug located at the right hand side of the stand to any 110 volt single phase line. The test stand will draw 4 amperes maximum. (Figure 3-1, location "a")

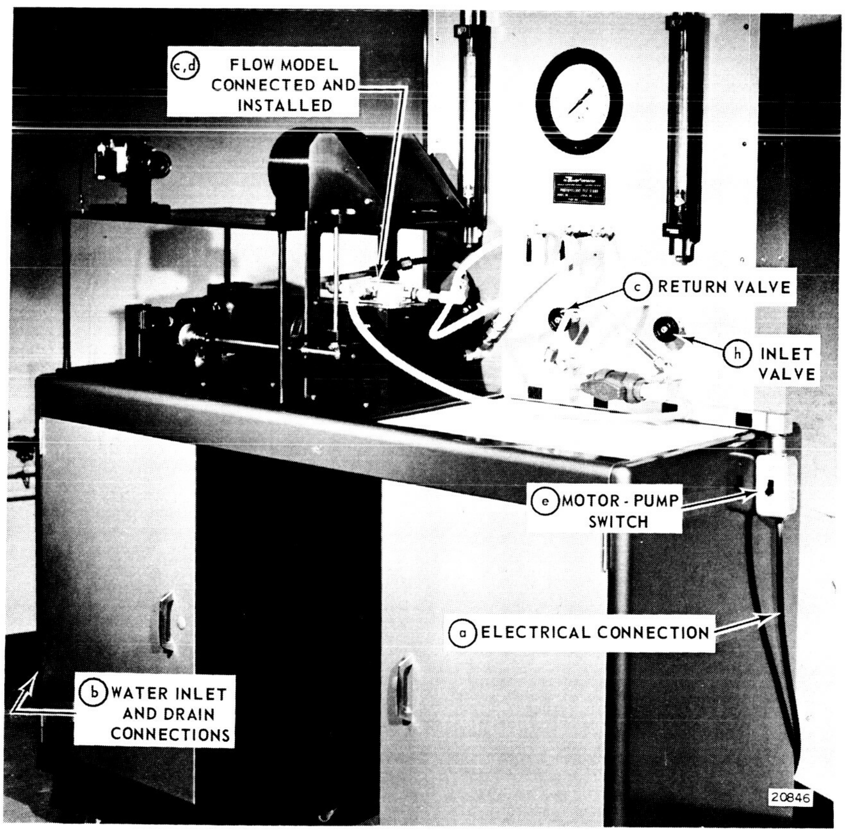

Figure 3-1 - Overall View of the Test Stand

2. Connect hot and cold water supply lines to the AN-4 fittings marked "Hot Water In" and "Cold Water In" located on the left hand side of the cabinet. Connect a line from a convenient drain or sink to the AN-8 fitting marked "Drain," also located on the left hand side. (Figure 3-1, location "b")

3. Install the test model in the flow circulation system by connecting the input line from the model to the AN-8 fitting located on the "T" of the three way manual valve on the right hand side of the gage panel. If another input is required, connect this line to the AN-8 fitting, located on the lower left hand side of the test panel. Connect the output line from the model to the AN-8 fitting, located at the lower center of the panel. Make sure that the valve located directly above this outlet fitting is opened at least part way before starting the pump. (Figure 3-1, location "c")

4. Install the test model in the polaroid fixture, making sure that the flow area under investigation is centered in the circular opening in the fixture. (Figure 3-1, location "d")

5. Turn on motor switch located at the right hand side of the test stand. (Figure 3-1, location "e")

6. Open valves supplying hot and cold water to the stand to the maximum position.

7. Turn on switch located on light source assembly at the left hand corner of the test stand. (Figure 3-2, location "g")

8. Open the valves located above the inlet fittings. Adjust the valves until the desired flow rate readings are obtained in the flowmeters. (Figure 3-1, location "h")

9. Adjust the knurled knob on the mixing valve (located in the left hand cabinet) until the desired temperature can be read from the thermometer, located in the right hand supply line. Clockwise rotation gives an increase in fluid temperature, while a counter clockwise rotation decreases temperature. (Figure 3-3, location "i")

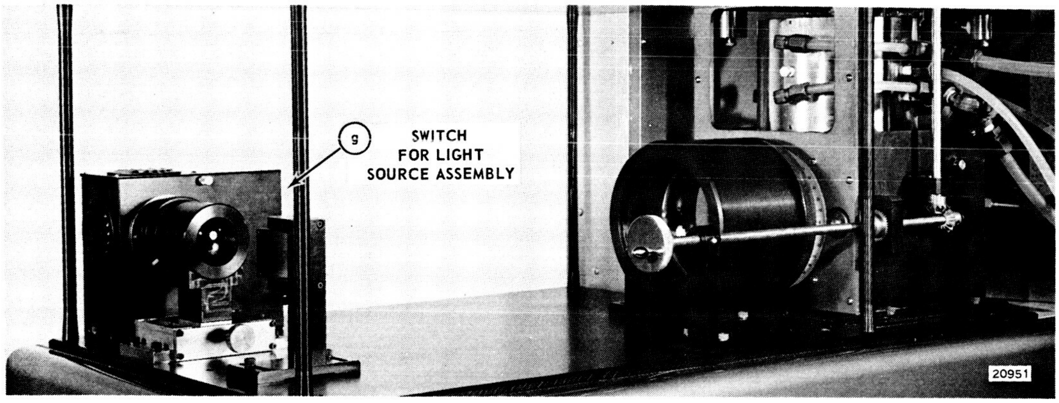

Figure 3-2 - Lower Level Optic and Polaroid Fixture

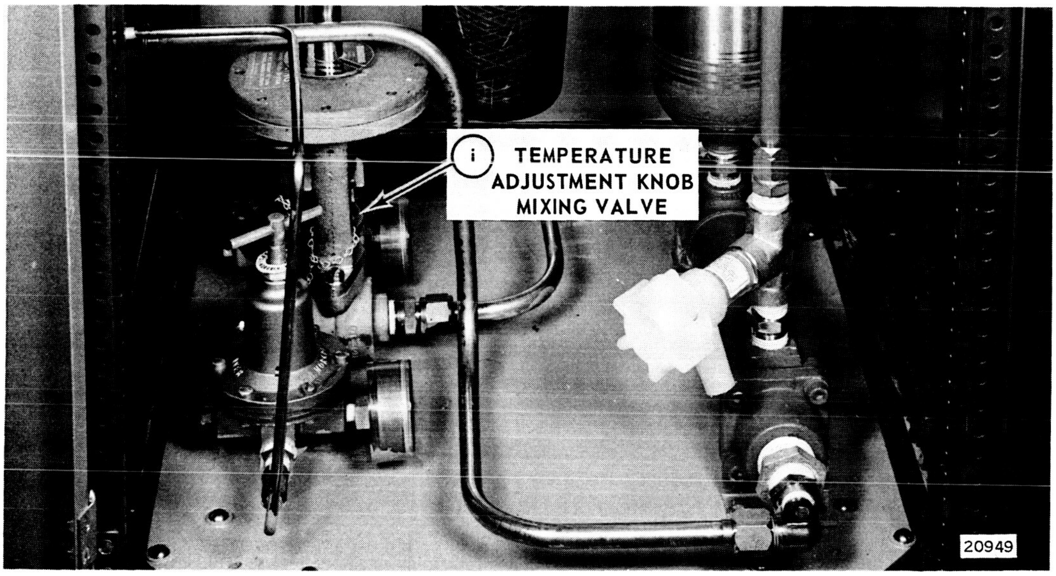

Figure 3-3 - Left Hand Cabinet Mixing Valve, Heat Exchanger Settling Tank and Filter is Installed

10. If photographs are to be taken of the fringe patterns, install camera on the fixture located at the left end of the upper optical level. Adjust the depth of field until a sharp pattern of the fringes is visible. To ensure good exposures, take pictures at various shutter speeds.

SECTION 4

MAINTENANCE

The Bendix Photoviscous Test Stand is relatively maintenance-free. Under normal operation, only the light source and the fluid filter element (Culligan "Filter-gard" element No. 9553-11) will require attention. The filter element should be changed every time the fluid is changed, and the light source will require a new bulb (Sylvania 15 hour, 150 watt, 120 volt, projection-type) for every 15 to 20 hours of testing.

SECTION 5

LIST OF EQUIPMENT

Component	Description	Supplier
Projection lamp	Sylvania 15 hour, 150 watt 120 volt, Tru-focus projection lamp; stock no. 50189	Edmund Scientific Co. Barrington, New Jersey
Focus lens	Eyelens, coated, 46 mm diameter, 78 mm focal length; stock no. 6247	Edmund Scientific Co. Barrington, New Jersey
Heat filter	Fish-Shurman heat interference type; XUR-96	Conductron Corporation Ann Arbor, Michigan
Monochromatic filter	Bausch and Lomb; 5461 Angstrom	Conductron Corporation Ann Arbor, Michigan
Polarizing sheets	Standard optic 66T lamination, non-ground and polished, 4 in. diameter; type HN CP37	Polaroid Corporation, Cambridge, Mass.
Collimating lenses	Air spaced achromatic lens, 133 mm diameter, 508 mm focal length; stock no. 70575	Edmund Scientific Co. Barrington, New Jersey
First surface mirrors	Selected plate glass coated with 601 first surface alloy, 4 in. x 6 in.	L. H. Sampson Company Farmington, Michigan
Pump and motor combination	Oberdorfer centrifugal pump; No. 4GCC, 1/3 h.p.	Chas. A. Strelinger, Warren, Michigan
Temperature Controller	Temperature control mixing valve.type 101 without regulators; Type B bulb	Jordan Corporation Cincinnati, Ohio

Component	Description	Supplier
Heat exchanger	Shell and tube type; model no. OCW-1-10	Vickers, Inc. Troy, Michigan
Regulator	Model no. 11-009-041; 0-160 psi	Norgren Company Denver, Colorado
Filter	"Filter-Card", model no. 9553-00	Culligan Filter Detroit, Michigan
Filter element	Replacement element, model no. 9553-11	Culligan Filter Detroit, Michigan
Three-way valve	Pattern no. 4555, 1/2 in inlet, 1/2 in x 1/2 in outlet threaded, PVC-1	Tamco Plastic Supplies Lima, Ohio
Reservoir	5 gallon capacity; model no. 2318-3	Tamco Plastic Supplies Lima, Ohio
Flowmeters	Model no. FP-1/2-27-G 10A3565A, % scale; float no. 1/2 GN SVT-48	Fischer-Porter Compan Detroit, Michigan
Pressure gage	Master test type 200, 0-30 PSI, 0.1 PSI Subdivisions	Marsh Instrument Co. Skokie, Illinois
Thermometer	Model no. S80775, viscosity, Engler, ASTM No. E-1, Centrigrade	E. H. Sargent Detroit, Michigan
Cabinet components		Amco Engineering, Chicago, Illinois
(a) Basic Frame	#FB28-19-22	Amco Engineering, Chicago, Illinois
(b) Side Panel	#SK28-22	Amco Engineering, Chicago, Illinois
(c) Knee space panel	SK22	Amco Engineering, Chicago, Illinois

Component	Description	Supplier
Cabinet components (continued)		
(d) Plain panel 28"	P28	Amco Engineering, Chicago, Illinois
(e) Working frame	FW22	Amco Engineering, Chicago, Illinois
(f) Hinged door, left	D28L	Amco Engineering, Chicago, Illinois
(g) Hinged door, right	D28R	Amco Engineering, Chicago, Illinois
(h) Base cowling	CB19	Amco Engineering, Chicago, Illinois
(i) Cowling, triple length	C90T	Amco Engineering, Chicago, Illinois
(j) Working surface, triple length	WS 22T	Amco Engineering, Chicago, Illinois
(k) Regular casters	CAX2S	Amco Engineering, Chicago, Illinois
(l) Locking casters	CAX3	Amco Engineering, Chicago, Illinois
Motor Vibration damper	5/16" isomode pad	MB Electronics New Haven, Connecticut